NASA Contractor Report 185295

Definition of Experiments to Investigate Fire Suppressants in Microgravity

James J. Reuther
Battelle
Columbus, Ohio

December 1990

Prepared for
Lewis Research Center
Under Contract NAS3-25362

National Aeronautics and
Space Administration

(NASA-CR-185295) DEFINITION OF EXPERIMENTS TO INVESTIGATE FIRE SUPPRESSANTS IN MICROGRAVITY Final Report (Battelle Columbus Labs.) 64 p   N91-14378
CSCL 22B   Unclas
G3/18   0323976

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SUMMARY

Defined and justified in this report are the conceptual design and operation of a critical set of experiments expected to yield information on suppressants and on suppressant delivery systems under realistic spacecraft-fire conditions (smoldering). Specific experiment parameters are provided on the solid fuel (carbon), oxidants (habitable spacecraft atmospheres), fuel/oxidant supply, mixing mode, and rate (quiescent and finite; ventilated and replenishable), ignition mode, event, and reignition tendency, fire-zone size, fire conditions, lifetime, and consequences (toxicity), suppressants (CO_2, H_2O, N_2) and suppressant delivery systems, and diagnostics. Candidate suppressants were identified after an analysis of how reduced gravity alters combustion, and how these alterations may influence the modes, mechanisms, and capacities of terrestrial agents to suppress unwanted combustion, or fire. Preferred spacecraft suppression concepts included the local, near-quiescent application of a gas, vapor, or mist that has thermophysical fire-suppression activity and is chemically inert under terrestrial (normal gravity) combustion conditions. The scale, number, and duration (about 1 hour) of the proposed low-gravity experiments were estimated using data not only on the limitations imposed by spacecraft-carrier (Shuttle or Space Station Freedom) accommodations, but also data on the details and experience of standardized smolder-suppression experiments at normal gravity. Deliberately incorporated into the conceptual design was sufficient interchangeability for the prototype experimental package to fly either on Shuttle now or Freedom later. This flexibility is provided by the design concept of up to 25 modular fuel canisters within a containment vessel, which permits both integration into existing low-gravity in-space combustion experiments and simultaneous testing of separate experiments to conserve utilities and time.

1.0. INTRODUCTION

When humans venture into space for exploration and development, they will not only have to conquer the new challenges posed by the extraterrestrial environment, but also those terrestrial challenges inherent in and attendant to the earth-like environment recreated aboard spacecraft for survival. **Fire safety is one of those challenges.**

This report presents the final results of a three-task project in spacecraft fire-safety research by Battelle for the National Aeronautics and Space Administration (NASA) Lewis Research Center under Contract No. NAS3-25362. The project was a component of the NASA Office of Aeronautics and Exploration Technology (formerly Office of Aeronautics and Space Technology) In-Space Technology Experiments Program (IN-STEP).

The objective of this project was to define specific in-space technology experiments that would identify, evaluate, and develop effective, practicable fire suppressants and suppressant delivery systems that either continuously prevent unwanted ignitions from occurring in manned spacecraft through atmosphere control, or quickly and permanently extinguish unwanted smoldering or flaming combustion, once initiated, with the action taken being no more life- or mission-threatening than the fire itself. This objective was approached through the following **project plan**:

Task 1. Analysis of Experiment Concepts
- 1.1. Identification of Spacecraft Fire Scenarios
- 1.2. Evaluation of Fire-Suppression Concepts

Task 2. Experiment Definition and Justification
- 2.1. Definition of In-Space Science Requirements
- 2.2. Justification for In-Space Experiments

Task 3. Definition Completion and Implementation Plan Development
- 3.1. Completion of Defined In-Space Experiment(s)
- 3.2. Preparation of Implementation Plan.

The information required for this project was obtained solely from a comprehensive and critical review of the technical literature available on space- and Earth-based combustion and its suppression. No experiments were conducted.

This report presents the results of this three-task research project, including the conceptual review, experimental parameters, and implementation plan for experiments on fire suppression in space. The proposed design of an in-space flight apparatus provides the means to simulate various situations representative of plausible spacecraft fire scenarios, after which various technologies can be used to deliver and evaluate the fire-suppression effectiveness of various agents. The following body of the report is organized into three sections to discuss the progress made on each of the three tasks outlined in the project plan. The sections are self-contained with separate references provided at the end of each section.

2.0. REVIEW OF SUPPRESSION CONCEPTS FOR SPACE

This section presents the results of Task 1 efforts on the project. The specific objective of Task 1 was to recommend no less than two spacecraft fire-suppression concepts for further development in terms of in-space technology experimentation.

2.1. Literature Review

Technical information was sought that would provide answers to the critical questions posed in Table 2.1. Question No. 1 established the pertinent technical literature. Questions No. 2 to 5 addressed the issues of reduced-gravity fires and their suppression, based on a review of Question No. 1 literature. Questions No. 6 and 7 established the conclusions and recommendations of the author, based on the preceding questions.

2.2. Technical Information (Question No. 1)

The references for this report section are to be found in Subsection 2.10. References 1 to 29 are a chronological bibliography of the technical documents thought relevant to Task 1 in terms of low-gravity combustion and fire safety; references 30 to 48 are a chronological bibliography of the technical documents thought relevant to the field of normal-gravity (terrestrial) fire suppression. Table 2.7, to be found at the end of Section 2.0, is

TABLE 2.1. CRITICAL QUESTIONS ON FIRE SUPPRESSION IN SPACE

No.	Questions
1	Is technical information available with which to evaluate potential spacecraft fire suppressants?
2	Based on the phase, amount, and configuration of flammable materials and the specifications of the oxidizing atmospheres to be expected on manned spaceflights, what is the nature of those fire situations, or scenarios, that have a reasonable probability of occurrence?
3	How and to what extent does low gravity alter the physicochemical characteristics of normal-gravity combustion?
4	How and to what extent do variables other than gravity influence the effectiveness of normal-gravity fire suppressants?
5	What candidate spacecraft fire suppressants have been identified and recommended, and why?
6	Have the alterations to combustion caused by reduced-gravity effects been adequately factored into the selection criteria for and analysis of spacecraft fire suppressants and atmosphere-inerting gases, and if not, what were the consequences of this omission on the selection?
7	Based on the information available and its application, can an effective, interim, spacecraft fire suppressant be recommended with confidence?

an annotated bibliography of the documents cited, constituting a response to Question No. 1.

Several papers and reports cover the topic of spacecraft fire safety and discuss fire suppression in particular.[15-18,26,28] These documents provided important background material for this study, which will be summarized and selectively used here. In addition, the author reviewed the preliminary findings of the International Microgravity Combustion Workshop, held at the NASA Lewis Research Center, January 1989, but the published proceedings of the workshop were not available at the time of writing of this report.

2.3. Spacecraft Fire Scenarios (Question No. 2)

To date, the principal approach by NASA to spacecraft fire safety has been prevention (**design to preclude**) by limiting the amount of onboard flammable material and controlling potential ignition sources[25]. Obviously, spacecraft fire safety cannot depend completely on protection by fire prevention. The avoidance of onboard flammable materials and combustion is impractical for advanced spacecraft, such as the Space Station **Freedom**[25,28], because of the complex, permanent operations and the variety of onboard experiments and operations planned. There are also serious questions on the definition of flammability standards for space and on the adequacy of controls and storage for waivered flammable articles. Hence, the situation regarding the possibility of fire aboard **Freedom**, with its Earth-like atmosphere, is that the **risk of an unwanted fire is finite**, and cannot be reduced to zero[15c,18]. Because of the variety of necessary materials and experimental procedures, it is likely that almost all types and classes of combustion--from smoldering to flaming--could occur aboard the Space Station **Freedom**.

A consensus from the review of available technical literature is that a plausible spacecraft fire scenario begins with the smoldering of deep-seated solid flammable material as the result of the overheating of electrical components[7,14,15,18,25,29]. A secondary and much less likely combustion (flaming) and explosion threat is from the evolution of a most readily ignitible gas, H_2, from either smoldering or the environmental control and life support system (ECLSS).

2.4. Effect of Gravity on Combustion (Question No. 3)

The reduced-gravity environment of orbiting spacecraft alters the physicochemistry of normal-gravity combustion by eliminating natural convection, affecting mass and energy transport. Low-gravity combustion has been the subject of extensive analyses and limited experiments (in drop towers, parabolic airplane flights, and spacecraft). Table 2.2 summarizes the observed effects of low gravity on diffusion and premixed flames. Some general differences in the gravity effects on the two modes of combustion may be noted. Table 2.2 is merely a generic compilation, with no distinction made of fuel type, equipment, and procedures, which undoubtedly influence the results to some extent.[35,46]

2.5. Factors Influencing Flame Suppressant Effectiveness (Question No. 4)

In the past, thick, flat normal-gravity flames have been used to simulate zero-gravity combustion on Earth,[2] by altering their normal-gravity

TABLE 2.2. GENERIC EFFECTS OF LOW GRAVITY ON DIFFUSION AND PREMIXED FLAMES

Flame Parameter	Change	Magnitude of Change	Reference(s)
		Diffusion Flames	
Spread Rate	Slower	~50%	1-3, 28
Luminosity (Sooting)	Brighter Dimmer	--	2-4, 17-19, 28
Thickness	Thicker	~50%	2-5, 7b, 19, 28
Burning Rate	Slower	~50%	3-5, 19, 27-28
Temperature	Cooler	--	3, 4, 17, 18, 28
Standoff Distance	Further	--	6, 9, 28
		Premixed Flames	
Luminosity (Sooting)	None	--	8
Burning Velocity	None	--	7c, 8, 11
Temperature	Hotter	--	10, 12
Standoff Distance	Further	--	12
Flammability Limits	None Wider	--	8, 11 7c
Ignition Energy	None	--	9, 11
		All Flames	
Extinction Mechanism	More Radiation Dominated	--	2, 8, 13, 23, 24, 27

combustion characteristics to correspond to those described for low-gravity flames in Table 2.2. As a specific example, note that the flame-front thickness of normal-gravity atmospheric, stoichiometric CH_4/air flames is increased by 50 percent upon either lowering gravity to the order of 10^{-4} m/s^2 (10^{-5} g) or by reducing pressure to 50 kPa (0.5 atm).[4,35] This suggests that low-gravity spacecraft fires may be (partially) simulated on Earth by subatmospheric flames. Thus, a first-order prediction of flame suppressant effectiveness in low-gravity fires may be made from the corresponding effectiveness in normal-gravity low-pressure flames, or at least on flames showing the characteristics of low-pressure flames. These characteristics are shown in Table 2.3, which documents the reduction in suppressant effectiveness as interpreted from a review of the literature.

TABLE 2.3. FACTORS INFLUENCING FLAME SUPPRESSANT EFFECTIVENESS

Flame Suppressant Effectiveness Is **Reduced** As:	Reference(s)
Flame Luminosity Increases	31
Flame Thickness Increases	37, 41, 43
Burning Rate (Speed) Slows	31, 32, 34, 40
Flame Temperature Cools	31, 32, 40, 45
Flame Standoff Distance Increases	37, 41, 43
Combustion "Air" O_2 Content Decreases	33, 34

2.6. Candidate Spacecraft Fire Suppressants (Question No. 5)

Because there is little time for low-gravity testing of potential spacecraft fire inerting and suppressing technologies before Space Station **Freedom** is designed, built, and flown, the effort to identify a workable interim technology has been quite active. A review of the literature provides recommendations for several candidate agents for spacecraft fire suppression worthy of immediate research consideration. For active agents, that is, fire extinguishants to fight a spacecraft fire once initiated, recommended agents include water, nitrogen, Halon 1301 (CF_3Br), carbon dioxide, and water-based foams.[15,18,25,28,29] For passive agents, atmospheric diluents to prevent fires, recommended gases include N_2, CO_2, He, CF_4, and SF_6.[15,16,18,25]

For the active agents, the rationale for selecting any particular candidate suppressant to date has been based on a set of qualifications, generically listed in Table 2.4. Also given in Table 2.4 is a summary, necessarily subjective, of the limited or severe drawbacks as applied to the various agents and their qualifications. Only one study to date has attempted a **quantitative** evaluation of spacecraft extinguishants on a systems basis.[18] Most of the qualification factors and assessments are obvious. Toxicity is distinguished between that of the neat (unreacted) agent and that of the combustion and extinguishment products. Compatibility with the spacecraft environmental control and life support system (ECLSS) recognizes that the system can cope with a modest overload of water and CO_2, but not with Halon 1301 or its byproducts. Physical cleanup of non-gaseous agents, such as water and foam,

TABLE 2.4. QUALIFICATIONS FOR ACTIVE SPACECRAFT FIRE SUPPRESSANTS

Qualification	Negative Factors* H_2O	N_2	CF_3Br	CO_2	Foam
Effectiveness Against all Fires	o	o	o	o	o
Effectiveness Against Smoldering		o	•		
Effectiveness on Mass Basis	o	•		•	o
Toxicity in Neat Form			o	o	
Toxicity of Products			•	o	o
Compatibility with ECLSS			•		o
Ease of Physical Cleanup	•		o		•
Post-Fire Electronic Recovery	•				o
Feasibility of Delivery at Low Gravity	•		o	o	•
Effect of Delivery on Fire	•			o	
Replenishability After Fire			•	o	•

*Extracted from Refs. 1, 14-18, 25, 28.
o Limited drawback.
● Severe drawback.

may pose a severe problem in space. Again, much study must be given on how to deliver the non-gaseous agents to the flame, without any assistance from gravity (no downward sprinklers, for example). It is also feared that the momentum of liquid delivery may scatter and spread low-gravity fires. Each candidate, therefore, has serious drawbacks as well as potential advantages. Table 2.5 summarizes the author's opinion of the primary and secondary disadvantages of each of the candidate active extinguishants.

TABLE 2.5. PRIMARY AND SECONDARY DRAWBACKS OF ACTIVE SPACECRAFT FIRE SUPPRESSANTS

Suppressant	Drawback: Primary Reason	Secondary Reason
H_2O	Uncertain delivery methodology	Gravimetric ineffectiveness
N_2	Gravimetric ineffectiveness	Fire applicability
CF_3Br	Toxicity	ECLSS incompatibility
CO_2	Gravimetric ineffectiveness	Toxicity
Foam	Difficulty of physical cleanup	Uncertain delivery methodology

The qualifications and drawbacks of the candidate passive oxygen-inerting gases have not been analyzed or debated extensively enough to provide a complementary table, primarily because of a lack of information on CF_4 and SF_6. Each inertant remains a candidate, although N_2 is championed for the obvious reasons that it is already the established diluent in the "air" atmospheres of spacecraft and has had precedential application in submarines.[15]

2.7. Selection of Fire Suppressants Based on Low-Gravity Combustion Knowledge (Question No. 6)

The previous subsections answered Critical Questions No. 1-5 (Table 2.1) by reviewing the technical literature to discover and categorize information in a particular manner. This information will now be used to answer Critical Question No. 6.

2.7.1. Active Fire Suppression

Considered first is what would be done actively to fight a spacecraft fire, once initiated, using low-gravity combustion as a guide.

It must be distinguished that not all the qualifications for spacecraft fire suppressants listed in Table 2.4 have a dependence on the artifacts of low-gravity combustion. Factors, such as toxicity, ECLSS compatibility, electronic component recovery, and replenishment are critical attributes required to meet the limited space and resources of **Freedom**. Post-fire cleanup is a general issue, but cleanup techniques involving mass transport may be influenced by the absence of natural convection at low gravity. Present spacecraft technology recognizes that liquid and mixed-phase extinguishants, such as water and foams, pose formidable delivery and cleanup problems yet to be solved. Likewise, the toxicity and corrosivity of the extinguishment byproducts of CF_3Br use make this agent an unlikely candidate for the Space Station **Freedom**. The present provision for CF_3Br on the Shuttle can be justified because, for short missions with immediate rescue opportunities, post-fire cleanup can be accomplished on the ground, eliminating on-orbit toxicity and corrosivity concerns.

With respect to the qualifications affected by reduced gravity, nevertheless, it is clear that the effects of reduced gravity have not been adequately or appropriately factored into the selection or validation process for spacecraft fire suppressants. A direct comparison of how and to what extent reduced gravity alters normal-gravity combustion (Table 2.2) with those factors that reduce the terrestrial effectiveness of common fire suppressants (Table 2.3) suggests that reducing gravity results in combustion that known terrestrial agents are less effective at suppressing. Thus, the following can be stated:

- Qualifying or disqualifying a candidate spacecraft fire suppressant on the basis of comparative normal-gravity effectiveness may be flawed and unfairly bias the results, unless it can be proven that the reduction in suppressant effectiveness at spacecraft conditions is the same for all agents and all fire scenarios.

A previous review by the author[41] showed that all fire suppressants demonstrate both chemical and physical activity, to some extent. An important question for spacecraft fire safety is whether the usual (terrestrial) modes and mechanisms for fire suppression are altered by low-gravity conditions. Recent drop-tower studies on paper combustion note that the extinction mechanism for low-gravity flames is dominated more by physical processes, particularly heat losses, than by chemical kinetics.[49] While extinction limits are by no means a complete analog for the prediction of active fire-extinguishment mechanisms, the author's review of documented data supports a strong argument for the dominance of thermophysical-suppression rather than chemical-suppression activity in low gravity. In other words, chemically active suppressants have more effectiveness to lose than physically active ones and, as gravity is reduced, the suppression effectiveness of chemical agents (CF_3Br) might approach that of physical agents (H_2O, N_2, and CO_2).

A further analogy may be noted from documented evidence that solid-phase extinguishants show a temperature dependence on effectiveness in normal gravity:

- At low temperatures (~500 C), efficient chemically active "dry chemical" powders, such as $NaHCO_3$, are no more effective than inert powders, such as CaO.[45]
- At high temperatures (~3000 C), chemically active CF_3Br is no more effective than inert CO_2.[44]

Such lower and upper temperature limits for suppressant effectiveness may provide an analogy for plausible spacecraft fire scenarios:

- Low-temperature (500-1000 C) smoldering combustion, and
- High-temperature (>2000 C) hydrogen combustion.

Further evidence may be advanced to support the arguments for the predominance of thermophysical suppression mechanisms in space. These are:

- Use of the normal-gravity approximation (low-pressure) of low-gravity combustion for an indirect proof.
- Comparison of the suppression effectiveness of various agents at normal- and low-gravity conditions for a direct proof.

With regard to the indirect proof, Table 2.6 documents that the suppression effectiveness of CF_3Br is significantly reduced in simulated low-gravity flames. In fact, the inhibition effectiveness of CF_3Br and N_2 was comparable and negligible in slow-burning (2-10 cm/sec), very cool (750 C) premixed CH_4 flames.[32]

With regard to the direct proof, early drop-tower tests determined that about 5 percent CF_3Br was ineffective at suppressing reduced-gravity solid-surface flames,[1] whereas normal-gravity studies indicate that this quantity is more than adequate.[40] Recent drop-tower tests on premixed CH_4/air flames determined that about 6 percent CF_3Br was necessary for complete suppression at low gravity, whereas at normal gravity, 2.5 to 4.3 percent could accomplish the same.[11,40,43] In summary, direct and indirect

TABLE 2.6. ESTIMATED LOSS IN SUPPRESSION EFFECTIVENESS OF CF_3Br UNDER CONDITIONS REPRESENTATIVE OF LOW-GRAVITY FLAMES

Fuel	Simulation of Reduced-Gravity Effect on Combustion	Reduction in Suppressant Effectiveness	Ref.
CH_4	Sootier, slower, cooler	70%	31
CH_4	Slower, cooler	6X	32
CH_4	Cooler	4X	40
CH_4	Slower	20-35%	40
C_2H_4	Thicker	50%	43
H_2	Slower, cooler	14%	34
CH_4	Thicker	45%	37
CH_4	Thicker	15%	41

information strongly suggests that **reduced-gravity causes parity in the ability of various agents to suppress combustion, meaning that normal-gravity suppression effectiveness is not a useful discriminator to qualify spacecraft fire suppressants.** Thus, the effectiveness of H_2O, N_2, and CO_2 can approach that of CF_3Br in spacecraft on a mass basis.

Nevertheless, if candidate suppressants are near-equivalent in their "universal" applicability, differences may emerge in their ability to suppress a most-probable spacecraft fire, i.e., smoldering. Smoldering, however, is a combustion event more likely to be prevented through atmosphere inerting rather than being terminated by suppression.[7d,15d]

2.7.2. Passive Atmospheric Inerting

Considered next is what might be done passively to prevent a spacecraft fire through atmospheric control, using low-gravity combustion as a guide. The technical merits and demerits of "suggested" oxygen-inerting gases have not been debated extensively; hence, there is no atmosphere-inerting versions of Tables 2.4 and 2.5.

Because atmosphere inerting is a continuous, passive fire-safety measure, whereas fire suppression is an active, "on-demand" one, the technology for its implementation is more integral to the total operating spacecraft system, especially the life-support system.[16-18,28] Detailed analyses of spacecraft structural design and weight factors, as well as their associated costs, were beyond the scope of this project. However, it is known that critical decisions on the value of recognized atmosphere-inerting systems must be made with some urgency, as a "point-of-no-return" in the design and construction of the Space Station **Freedom** is rapidly approaching. For this reason, serious attention was given to the atmosphere-inerting portion of Critical Question No. 6.

Again, it is clear that the effects of reduced gravity have not been satisfactorily factored into the selection or validation process for spacecraft atmosphere-inerting gases. Atmospheric-inerting technologies, such as N_2-flooding, known to have some protective value in the confined spaces of submarines and aircraft, may not have the same effectiveness in the low-gravity environment of spacecraft. Consider the following qualitative information as the first justification for this conclusion, especially with regard to the most feasible concept of N_2-inerting technology:

- Inerting may not impede the progress of low-temperature (300 C) smoldering.[47]
- Inerting may not suppress smoldering at reduced gravity because the flammability limits of the principal products of smoldering, CO and H_2, may be altered.[7d]

The first supposition is based on the results that N_2 had little effect on slow-burning, cool (750 C) CH_4-flames.[32] The second supposition is an indirect conclusion from modeling studies of simulated low-gravity combustion, which indicated that changes in the partial pressure of oxygen did not alter flame extinguishment parameters significantly.[2] Furthermore, experimental studies at low-gravity conditions indicated that 88 percent N_2 was required to inert H_2-flames,[23] whereas studies at normal gravity indicated that only 71 percent was required, implying that N_2-inerting was 24 percent less effective in low-gravity environments.[46] The latter number refutes qualitative claims that modest reductions in spacecraft atmospheric oxygen content (N_2 increase) would give a substantial increase in fire protection.[15c,15d] Additional, albeit indirect, support for this apparent loss in effectiveness of

N_2-inerting comes from simulated (low-pressure, normal-gravity) low-gravity combustion where the apparent effectiveness of N_2 to suppress combustion is reduced by 14-45 percent, compared to that at atmospheric pressure.[37,41]

As an addendum to these observations on inerting ineffectiveness, the author suggests that N_2-inerting of spacecraft environments for passive prevention of ignition may jeopardize the ability for active fire suppression. This is because experiments have demonstrated that the effectiveness of one halogenated suppressant (HBr) was reduced by 75 percent as the oxygen content of the combustion air was reduced from 22 to 16 percent.[33] Furthermore, the actual "inertness" of various candidates under smoldering conditions may be questioned in view of the fact that chemicals, such as SF_6, thermally decompose at lower, smoldering-like temperatures (600-800 C) in the presence of surfaces, thus producing toxic byproducts.[48] In summary, atmosphere-inerting of low-gravity spacecraft environments may not provide the same degree of fire safety that it does in confined environments at normal gravity.

2.8. Recommended Spacecraft Fire Suppressants (Question No. 7)

Based on the preceding review, one may establish the following critical requirements for spacecraft fire suppressants:

- Must not pose a prohibitive mass penalty in stored form.
- Must have a volumetric effectiveness such that a quantity sufficient to inert or suppress multiple or large-scale fires can be transported, stored or replenished, and delivered on demand.
- Must be deliverable via a method requiring low momentum in reduced gravity to avoid increasing the convective environment surrounding the fire.
- Must possess a negligible toxicity and corrosivity in neat form and be compatible with the environmental control and life support system (ECLSS) in the event of releases via false alarms.
- Must be active over the temperature range of 500-2000 C to be effective at preventing or extinguishing the expected variety of plausible spacecraft fires.
- Must act to enhance the normal extinction mechanism of low-gravity flames, which is dominated by radiation loss.

- Must generate byproducts upon action that are nontoxic and non-corrosive to spacecraft systems and removable via the ECLSS.

In short, prerequisites for practicable spacecraft fire suppressants favor gaseous agents that are chemically inert and deliverable at low momentum. These critical requirements for spacecraft fire suppressants allowed the following candidate fire-fighting technologies, and their mode of deployment, to be ranked according to a decreased probability of success, as follows:

- **CO_2 suppression by local application,**
- H_2O suppression by local application, and
- N_2 inerting by atmosphere control.

While this ranking appears reasonable and consistent with the preceding review and established criteria, its order was greatly influenced by the consideration of flame radiation effects.[16,17,25,26,28] Although subject to validation, the author believes that increasing the luminosity (sooting) of spacecraft fires may not have the effect of enhancing their extinction, but may instead enhance combustion via increased radiative feedback to the fuel surface. For a suppressant to be effective radiatively, it must decrease flame luminosity, act as a radiation sink itself, and remain transparent between the flame and its surroundings. On this basis, CO_2 was favored over N_2 because CO_2 decreases sooting in diffusion flames by 20-30 percent more than does N_2,[42] and CO_2 is more active radiatively (infrared) than N_2.[2] Moreover, CO_2 was favored over N_2 based on the results of analogous low-pressure studies.[36,41,46] Unlike N_2, CO_2 does not lose its apparent effectiveness as pressure is reduced in normal-gravity flames, implying that CO_2 may maintain its superiority in effectiveness over N_2 under low-gravity spacecraft conditions.

To reiterate, CO_2 is the first choice of a suppressant to investigate under spacecraft conditions, and to use in the interim, as some others have recommended.[18,25] H_2O was selected as a second candidate suppressant primarily because it must be distributed as a mist, a method of application the would be difficult and uncertain under low-gravity conditions.[2,15,29]

N_2-inerting was ranked behind CO_2 or H_2O-suppression primarily because of its relative ineffectiveness probably cannot prevent the most plausible spacecraft fire scenario: smoldering. The limiting O_2 content (after nitrogen inerting) for preventing the combustion of the CO and H_2 released upon smoldering is 5.0-5.5 percent, well below the minimum of 16 percent thought practicable and livable.

The aforementioned ranking summarizes the findings of Task 1 of the study. The selection of the three candidate agents was based on a review of data concerning conventional suppression techniques and low-gravity combustion behavior. Although technical information exists with which to propose and reasonably support the acceptability of interim spacecraft fire suppressants, Earth- and space-based experiments are urgently needed to increase confidence in such technologies.

2.9. Concluding Remarks on Review of Suppression Concepts (Task 1)

The objective of Task 1 was to recommend two or more spacecraft suppression concepts for further development (design) in terms of in-space technology experimentation. Such experimentation would identify, evaluate, and develop effective, practicable spacecraft fire suppressants and suppressant delivery systems, the overall objective of the program.

Information was obtained by proposing a set of critical questions, followed by using the literature on low-gravity combustion and on conventional fire suppression to provide answers by analogy, comparison, and/or extrapolation. The ground rules for practical spacecraft fire suppression and the underlying problems in the selection of candidate technologies are as follows:

- Most plausible spacecraft fire scenarios include low-temperature smoldering and high-temperature combustion of smoldering products.
- Effects of reduced gravity on combustion and how it influences conventional atmosphere inerting and fire suppression have not been adequately factored into the selection and validation process for spacecraft fire-fighting actions.
- Because of a low-gravity-induced loss in inerting and suppression effectiveness, agents that possess chemical suppression or

inerting activity in terrestrial flames may lose this activity in low-gravity flames, resulting in parity among candidate spacecraft fire suppressants.

Based on the findings of the Task 1 study and reasonable inferences, the author concludes the following:

- Practicable spacecraft fire suppressants must be effective, nontoxic, noncorrosive, ECLSS compatible, thermally and radiatively active, chemically inert over 500-2000 C, fluid (gaseous), and quiescently deliverable.

- Three extinguishing technologies, already established as state-of-the-art in normal gravity, meet most of the critical requirements. A preliminary ranking favors directed, localized suppression with CO_2 over H_2O-suppression or N_2-inerting as an interim spacecraft-fire-safety measure.

The second task of this project was to design the in-space flight apparatus that would allow these candidate suppressants to be evaluated. The results of the definition and justification of these spacecraft fire suppression experiments appear in Section 3.0 of this report.

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TABLE 2.7. CONTRIBUTION/SIGNIFICANCE OF INDIVIDUAL REFERENCES

Ref.	Contribution/Significance to Low-Gravity Combustion and Fire Safety Research
1	Pioneering drop-tower study on the effect of lowered gravity on the solid-surface fire-suppression efficiency of CF_3Br, protein foam, or atomized water, indicating: • All have a greatly diminished suppression efficiency as gravity is reduced from terrestrial levels, even with optimized delivery.
2	Use of thick, flat, normal-gravity diffusion flames to simulate zero-gravity combustion and infer information regarding the effect of gravity on combustion, reaching the significant conclusions that: • Increased radiative loss or CO_2 concentration in the flame zone would promote extinction, and • Changes in partial pressure of oxygen did not alter extinguishment parameters appreciably.
3	Detailed studies of laminar gas-jet diffusion flames at zero gravity, indicating: • Low-g flames are cooler, slower, thicker, and sootier than normal-g flames.
4	Continuation of Ref. 3, with the following quantitative information: • Lower gravity causes about a 50 percent reduction in burning rate.
5	Modeling of low-gravity laminar gas-jet diffusion flames, concluding: • Partial-oxidation models provide an improvement in the accuracy of predictions under zero-gravity conditions.
6	Theoretical study of low-gravity gaseous-diffusion flames demonstrating: • Flame standoff distance increases as gravity is reduced.
7	Review text describing results of past and planned zero-gravity combustion experiments to date (1981), including those on smoldering combustion that conclude that: • CO and H_2 are the principal products of smoldering, present at flammable concentrations, and smoldering may be more difficult to inert with N_2 at reduced-gravity.
8	Experimental study on the effect of gravity on laminar, premixed, stoichiometric and fuel-lean CH_4/air combustion, showing that: • Reduced gravity had little or no effect on lean flammability limit, burning velocity, flame color, or temperature.
9	Continuation of study in Ref. 8 reporting that: • The minimum ignition energies of CH_4/air flames were the same at normal and zero gravity.
10	Experimental study of premixed lycopodium/air flames at normal and reduced gravity, reporting that: • Peak flame temperature is 150-200 C hotter at zero gravity than at normal gravity.
11	Experimental study of the effect of CF_3Br and reduced gravity on laminar premixed CH_4/air flames, reporting: • CF_3Br inhibition was "slightly less effective at zero-g", • "About 6 percent rendered CH_4/air mixtures nonflammable under all conditions tested," and • 1.0-5.9 percent CF_3Br had no effect on CH_4/air flame velocity at 1 atmosphere and zero-g.
12	Continuation of Ref. 10, reporting: • Premixed flame standoff distance increases as gravity is reduced from 1-g.
13	Theoretical analysis concluding: • Low-speed forced-air flow (ventilation) at low gravity helps sustain combustion, and • Flame extinction is dominated by radiation loss.
14	Review of space station fire safety in a popular sense, indicating: • Onboard fire is the greatest fear, • A disabled environmental control and life support system (ECLSS) is the second, and • The ECLSS can generate flammable gases, such H_2 and CH_4.

TABLE 2.7. (Continued)

Ref.	Contribution/Significance to Low-Gravity Combustion and Fire Safety Research
15	Proceedings of a NASA spacecraft fire-safety workshop, the entire contents of which are significant.
16	Technical paper reviewing the details of Ref. 15.
17	Same as Ref. 16.
18	Systems analysis of fire suppression alternatives for the U.S. Space Station, recommending: • Portable CO_2 extinguishers for small localized fires and CF_3Br total-flooding for module-wide H_2 fires, based on a 5-point numerical (subjective) analysis of tradeoffs among effectiveness, toxicity, aftereffects, weight, and cost.
19	Experimental study of electric field-induced flame convection in the absence of gravity.
20	Bibliography on spacecraft fire detection and extinguishment, including related references on aircraft and submarine fire safety.
21	Study of industry requirements that can be fulfilled by combustion experimentation aboard Space Station, including fire extinguishment.
22	Spacecraft fire-safety experiments for the Space Station technology development mission, especially fire extinguishment at low gravity and at smoldering and deep-seated combustion conditions.
23	Experimental study of the role of chemical kinetics and transport in the extinction of premixed lean-limit flames of $H_2/O_2/N_2$ and $CH_4/O_2/N_2$ at normal and reduced gravity, offering: • Secondary data on the amount of N_2 required to inert microgravity flames of H_2 (88 percent) or CH_4 (80 percent), which, when compared to those in Ref. 46 for 1-g flames of H_2 (71 percent) and CH_4 (36 percent), clearly demonstrate the reduced inerting effectiveness of N_2 at low gravity and the resistance of these flames to physical extinguishment.
24	Study to develop and model the extinguishment mechanism of laminar premixed flames at microgravity, concluding: • Thermal transport is more important than chemical kinetics at extinction.
25	An update of the technical series begun with Refs. 16-17, including the points that: • Smoldering combustion may be more common and more probable at low rather than normal gravity, • No one type of extinguishant can satisfy all desirable criteria, and • CO_2 is the leading candidate for primary extinguishant aboard Space Station Freedom.
26	Program overview of NASA microgravity combustion science, updating Refs. 16, 17, and 25, including the impact (more intense, faster, sootier combustion) of slow, forced-air convection.
27	Study of the extinguishment of low-gravity premixed $H_2/O_2/N_2$ flames, reporting that: • "CF_3Br ... may not substantially reduce reactivity in ... very low-temperature ($H_2/O_2/N_2$) flames" and • "CF_3Br has much less of an effect on the burning velocity than dilution with air or N_2."
28	Review of spacecraft fire-safety applications, updating Refs. 15-17 and 25, all of which is significant.
29	Study of expert systems applied to spacecraft fire safety, including advocacy of foam extinguishers.
30	Data that CO_2 may chemically, rather than physically, inhibit premixed $H_2/O_2/N_2$ flames.
31	Data that CF_3Br inhibition effectiveness decreases by 70 percent as a premixed stoichiometric CH_4/air flame is made 30 percent fuel rich and flame velocity slows and temperature cools.

TABLE 2.7. (Continued)

Ref.	Contribution/Significance to Low-Gravity Combustion and Fire Safety Research
32	Data that the inhibition effectiveness of both N_2 and CF_3Br is comparably negligible in slow-burning (2-10 cm/sec), very cool (750 C) or very hot (2700 C) premixed CH_4 flames.
33	Data that the inhibition effectiveness of HBr decreases 75 percent as the oxygen content of air in premixed stoichiometric CH_4 flames is reduced from 22 percent to 16 percent.
34	Data on a CF_3Br-inhibited premixed fuel-rich (75 percent) H_2/O_2 flame which, when compared to those in Ref. 43, reveal a 14 percent decrease in CF_3Br inhibition effectiveness upon H_2 enrichment.
35	Data that the thickness of premixed stoichiometric CH_4/air flat flames increases by 50 percent as atmospheric pressure is reduced from 1 to 0.4 atmosphere.
36	Technical review of combustion suppression by vapor-phase agents providing data which, when combined to those in Ref. 46, indicate that CO_2 flame-inhibition effectiveness is not reduced as pressure is reduced.
37	Data on N_2-inhibited low-pressure (0.01 atm) stoichiometric CH_4/O_2 flames which, when compared to those in Ref. 41, reveal a 45 percent decrease in N_2 inhibition effectiveness upon lowering pressure.
38	Specialized technical review of fire suppression that provides quantitative measures for effectiveness of flame inhibition and extinction and modes of action by various agents.
39	Data that the minimum amount of CF_4 required to suppress H_2/O_2 flames is only about 8 percent less than that of N_2 (83.5 versus 90.5 percent, respectively).
40	Comprehensive technical review of halogenated fire suppressants, providing data indicating: • Cool (800 C) flames require 4-times more CF_3Br for extinguishment than hotter (1500 C) flames, • Slower-burning (by 50 percent) flames require 20-35 percent more CF_3Br for extinguishment, • Amount of CF_3Br required to inhibit CH_4/air flames is 4.3 ± 3 percent, and • CF_3Br can promote pyrolysis.
41	Specialized technical review with data which, when compared to those in Refs. 36 and 37, indicate that: • Flame inhibition effectiveness of N_2 decreases by about 15 percent upon lowering pressure (from 1 to 0.1 atm), whereas the inhibition effectiveness of CO_2 does not.
42	Data that the addition of CO_2 lowers the soot-forming tendency of premixed or diffusion flames of hydrocarbon/air more (20-30 percent) than does N_2.
43	Detailed chemical-kinetic modeling data, indicating that: • Flame inhibition effectiveness of CF_3Br is reduced 50 percent upon lowering the pressure of C_2H_4/air flames from 1 to 0.1 atm. • 2.5 percent is the amount of CF_3Br required to suppress all CH_4/air flames, and • CF_3Br is more effective in stoichiometric H_2/air flames at normal gravity than at low gravity (data in Ref. 11).
44	Detailed chemical-kinetic modeling data, indicating that: • CF_3Br is not as effective as CO_2 in reducing the detonation hazard of C_2H_4/air mixtures and • CF_3Br acts more as a detonation sensitizer than as an inhibitor.
45	Data setting precedence for the temperature dependence of inhibitor effectiveness.
46	Compendium of data on flammability limits, inerting requirements, minimum ignition energies and temperatures, quenching distances, and flame temperatures and burning velocities as a function of fuel and oxidant (air, oxygen, or oxygen- or nitrogen-enriched air).

TABLE 2.7. (Continued)

Ref.	Contribution/Significance to Low-Gravity Combustion and Fire Safety Research
47	Review of smoldering combustion, with information implying that: • Nitrogen-inerting may not impede the progress of low-temperature (300 C) smoldering.
48	Data indicating that the thermal decomposition temperature of alleged "inerts," such as CCl_4 and SF_6, is lowered to 600-800 C in the presence of refractory material.

3.0. EXPERIMENT DEFINITION AND REQUIREMENTS FOR SPACECRAFT FIRE SUPPRESSION

This section presents the results of Task 2 efforts on the project. The specific objective of Task 2 was to define the science requirements for and justify the in-space conduct of experiments designed to evaluate the low-gravity fire-suppression concepts identified in Task 1.

3.1. Literature Review

Technical information was sought that would provide answers to the critical questions posed in Table 3.1. Question No. 1 established the pertinent technical literature. Questions No. 2 and 3 addressed issues on in-space experiment requirements and justification, based on a data search and retrieval conducted on the technical literature.

TABLE 3.1. CRITICAL TASK 2 QUESTIONS FOR WHICH SCIENTIFIC INFORMATION AND ANSWERS WERE SOUGHT

No.	Questions
1	What technical information is available with which to assess the feasibility of adapting existing technologies for in-space combustion experimentation to meet the science requirements for in-space research on low-gravity fire suppression?
2	What are the basic science requirements for the proposed Task 1 in-space experiments on low-gravity fire suppression, specifically the scope, experimental parameters, scale of experiments, number and duration of tests, and other contributing factors?
3	What are other important in-space experiment considerations, such as the justification for the conduct of the experiment in space (as opposed to ground simulation), the influence on the proposed experiment of low-gravity quality, the maximum volume and power requirements, and the extent of crew involvement?

3.2. Technical Information (Question No. 1)

Initial efforts consisted of reviewing the technical literature available on how and to what extent low-gravity combustion experiments have been defined to date. This information and experience served as the technical foundation for the definition of the low-gravity fire-suppression experiments sought here.

The references for this report section are to be found in Subsection 3.6. References 1 to 27 are a chronological bibliography of technical documents relevant to low-gravity combustion experiments. The type of fuel and combustion studied in the low-gravity experiments conducted, or proposed, to date, is listed for each reference in Table 3.2. The most valuable sources for the review were those of references 6, 13, 17, and 18.

TABLE 3.2. LOW-GRAVITY COMBUSTION EXPERIMENTS BY FUEL AND FLAME TYPE

Fuel/Flame Type	References
Solid, Diffusion	1, 6, 12, 14, 17, 18, 22, 24, 25, 26, 27
Gaseous, Diffusion	2, 3, 4, 5, 12, 14, 15, 16, 17, 22, 24
Liquid, Diffusion	6, 12, 14, 22, 24
Gaseous, Premixed	6, 7, 8, 9, 10, 12, 14, 17, 19, 20, 22, 23
Solid, Smoldering	6, 12, 14, 18, 25, 26
Liquid, Droplet	6, 12, 13, 14, 15, 17, 22
Solid, Particulate	6, 9, 11, 12, 13, 14, 15, 17, 22

Some general observations on documented experience from low-gravity combustion research are as follows:

- The majority of the hardware developed has been for use in low-gravity experiments during which the combustion process itself is being studied, and not the ability to suppress it.

- The principal method for terminating the combustion process in prior experiments appeared, at best, to be a simple extrapolation of normal-gravity methods, or, at worst, an afterthought.

- Of the experiments during which fire-fighting at low-gravity conditions was of direct interest, the focus was mainly on the prevention or suppression of high-temperature flaming, and not low-temperature smoldering, combustion.

- On first inspection, it appeared that it was not feasible to develop a conceptual design for a definitive in-space fire-suppression experiment from the mere modification of the components that now accompany in-space combustion experiments for safety, and not research, purposes.

- While there is no shortage of general, often interchangeable, ideas on how and which spacecraft fire-suppression experiments might be performed, the science requirements for these experiments only been superficially defined.

These observations were, of course, influenced by the findings on suppression concepts of Task 1 (Section 2.0). The next subsection, which describes the science requirements for the spacecraft fire-suppression experiments proposed in Task 1, explains how.

3.3. Science Requirements for Spacecraft Fire-Suppression Experiments (Question No. 2)

The science requirements for the in-space experiments to investigate the fire-suppression concepts selected from Task 1 (Section 2.0) include the scope of the study, experimental parameters, scale of experiments, number and duration of tests, and other contributing factors.

3.3.1. Scope of the Study

The objective of the study described in this report was to define feasible, straightforward, versatile, and scalable experiments that yield the most timely, definitive, and practicable information on spacecraft fire suppressants and suppressant delivery systems according to the concepts established in the Task 1 review (Section 2.0). The suppressants identified to meet these qualifications were as follows, in decreasing order of merit:

- Carbon dioxide (CO_2) suppression by local application,
- Water (H_2O) suppression by local application, and
- Nitrogen (N_2) inerting by atmosphere control.

Before proceeding with the specifics of the proposed definition of experiments to investigate low-gravity fire suppression, one should note that the development of unambiguous guidelines for the experimental design and evaluation of safe and effective terrestrial fire suppression systems remains a difficult scientific challenge, even after several decades of effort.[28,29] Perhaps the best way to describe why this challenge exists is to state that the results of most tests are design-, device-, methodology-, and/or application-specific, which leaves data open to interpretation, at best, and suspicion, at worst. A universal, standardized methodology for the evaluation of any fire-suppression agent, along with its delivery system, in any new fire situation, simply does not exist, and may never. On a more optimistic note, however, one may observe that the situation-specific conditions posed by spacecraft environments offer a more favorable probability of designing a successful systems-evaluation experiment than those posed by general Earth conditions. (There is, after all, only one Space Station **Freedom**).

Finally, the definition of experimental parameters must address the age-old dilemma regarding experimental design. With respect to maximum accuracy and the avoidance of ambiguity in the resulting data, is it better to design experiments that sacrifice control and variability of parameters in favor of realism, or is it better to sacrifice realism via simulation and specify and vary experimental parameters independently?

3.3.2. Experimental Parameters

Table 3.3 lists experimental parameters specific to the low-gravity combustion-suppression experiments suggested in Section 2.0, as well as their general variability. The specifics of these experimental parameters are discussed next. Note that the establishment of these science requirements was an iterative process.

Fuel. Fuel holds first position in Table 3.3 because fuel specifications directly influence every other parameter in the experiment to study in-space fire suppression, affecting both the initial conditions as well as the boundary conditions.

Because of the requirement defined in Task 1 to recreate smoldering combustion, experimental fuel candidates were limited to solids. This fuel specification subsequently fixed the specifications for many of the other

TABLE 3.3. EXPERIMENTAL PARAMETERS FOR IN-SPACE SMOLDER-SUPPRESSION EXPERIMENTS

No.	Experimental Parameter	Variability
1	Fuel	Onboard flammable material(s)
2	Oxidant	Manned-spacecraft habitat(s)
3	Fuel/oxidant supplies	Finite or infinite
4	Fuel/oxidant mixing and rate	Quiescent (diffusion) or ventilated (low-velocity convection)
5	Ignition event and mode	One-time or continuing, thermal or electrical
6	Reignition tendency	None, immediate, or delayed
7	Fire zone size	Millimeters, centimeters, or meters
8	Fire conditions	Smoldering and/or flaming
9	Fire lifetime	Seconds or minutes
10	Fire consequences	Production of heat and combustion byproducts
11	Suppressant delivery	CO_2, H_2O, or N_2 volume and flow conditions
12	Diagnostics	Preflame, flame, and/or post-flame conditions

parameters, such as heat content, ignition characteristics, products of combustion, and so on.

Fuel specifications would be ideal if they had the qualities listed in Table 3.4. The technical literature on smoldering combustion, its creation and suppression, was reviewed to identify a fuel whose qualities approached these ideals. On this basis, carbon-based materials (chars, blacks, charcoals) were selected as most qualified to serve as the fuel in the proposed experiments on low-gravity smolder suppression.[6,31-38]

Table 3.5 lists the qualifications of carbon-based fuels for low-gravity smolder-suppression experiments. As should be deduced from the amount of data in Table 3.5, carbon smoldering and its suppression have been the subject of considerable terrestrial research. The in-space research proposed here should be complementary.[6,38]

Oxidant. The science requirements for the "oxidant" to be used in the proposed in-space smolder-suppression experiments have been influenced strongly by the atmosphere(s) being considered for the habitable environment aboard **Freedom**. Suffice it to say here that candidate atmospheres believed to support life and prevent fire aboard **Freedom** have been the subject of considerable debate.[6,12,14,15,18,21,24]

TABLE 3.4. IDEAL REQUIREMENTS FOR SOLID FUELS IN SPACECRAFT SMOLDER-SUPPRESSION EXPERIMENTS

- The physical characteristics should be such that its size, shape, density, and porosity can be readily varied.
- The chemical composition should be such that only combustible elements are present (no ash residue), with these elements controllable one or more at a time.
- The heat content should be reproducible to a high degree and sufficiently high such that only a relatively small quantity is required to create a fire and heat.
- The ignition characteristics should be such that ignition can be achieved in the absence of forced convection and varied over some appreciable range of minimum temperatures.
- The burning characteristics should be such that the minimum oxidation rate is slow (smoldering), symmetrical, self-sustaining, and selectable under quiescent flow conditions, and variable (increasing) under dynamic-flow conditions.
- The products of (smoldering) combustion should be such that they are minimum in number and somewhat controllable, yet still representative (prudently so) of spacecraft fire emissions in terms of consequences (toxicity, compatibility with life-support systems).
- The suppression characteristics under terrestrial, deep-seated fire conditions should be such that the largest quantity of the most effective agent is required.
- The combustion extinction characteristics should be such that some other safeguarding mechanism can be relied on to suppress the combustion if the fire-suppression agent being tested fails to do so.
- The candidate flammable material will be present aboard manned spacecraft, and could be the origin of a fire.

Life-support atmospheres may be varied in terms of partial pressure and mole fraction of oxygen, total pressure, and identity of the non-oxidant fraction. With regard to the latter, the Task 1 (Section 2.0) findings did not support the testing of any non-oxidant other than nitrogen, because other candidate diluents (e.g., sulfur hexafluoride, SF_6) have never been thoroughly investigated and may not, in fact, be inert under either terrestrial or spacecraft fire conditions.[48]

Thus, the variation of the oxidant amounts to a study of passive suppression technology by N_2 inerting (see Section 2.0). While the findings of Task 1 questioned the effectiveness of inerting technology, experiments are proposed here to obtain direct information on its feasibility. Furthermore, there is concern about the threat of fire within the hyperbaric chamber on **Freedom**, justifying experiments in at least one representative high total-pressure atmosphere.

TABLE 3.5. QUALIFICATIONS OF CARBON AS A CANDIDATE FUEL TO MEET IDEAL REQUIREMENTS

- Carbon-based materials can be molded into a variety of shapes and sizes, with considerable control over density and porosity.[31]
- Chars, blacks, and charcoals are typically 95% carbon, with the balance predominately inert (inorganic) ash, and can have their elemental composition altered by simple blending with other flammable solids.[34]
- At 32.8 MJ/kg (7,830 cal/g), chars, blacks, and charcoals are some of the more energy-dense flammable solids available.[34]
- The ignition temperatures of specific carbon blacks formed under different process conditions naturally vary from about 320 to 535 C, whereas the ignition temperature of specific carbon blacks can be varied from about 265 to 740 C via the impregnation of trace (parts per million) quantities of metal catalysts. Moreover, ignition can be achieved under quiescent conditions (no oxidant convection), and be enhanced by forced convection.[31,32,34,35]
- Once ignited, carbon-based materials smolder slowly ($\sim 1 \times 10^{-4}$ g/cm^2-sec) at near-constant temperatures ($\sim$500 C) in a manner that is quite symmetrical, self-sustaining under quiescent conditions, and accelerated by forced convection.[33]
- The oxidation rates of carbon-based fuels can be altered to vary over 5 to 6 orders of magnitude, with some of the more reactive carbons oxidizing at rates approaching 100s of milligrams per minute.[33,36]
- The (almost) exclusive products of carbon-based combustion (smoldering) are CO_2 and CO, which can be singly or simultaneously generated and which singly and collectively pose representative threats to the life of spacecraft crew and to the operation of life-support systems.[33,34,39]
- The self-extinction of carbon smoldering can be achieved not only by limiting the fuel and oxidant supply, but also by incorporating trace quantities of foreign solids, such as borates.[37]
- Charcoal has been used as a model, worst-case Class A fuel in standardized experiments to evaluate the effectiveness of gas-phase terrestrial agents to suppress deep-seated smoldering combustion, which indicate that a relatively high volumetric concentration (13%) of an effective agent (Halon 1301) is required to extinguish smoldering, whereas an even higher concentration (65%) of ineffective agent (CO_2) is required.[29]
- Activated carbons will probably be aboard Space Station Freedom as a component of the environmental control and life support system (ECLSS), which has been identified as a possible location for a fire.[39]

From the preceding assessments, the following oxidants are then proposed for low-gravity smolder experiments:

- 12% O_2 in N_2 @ 150 kPa (1.5 atm),
- 16% O_2 in N_2 @ 100 kPa (1.0 atm),
- 21% O_2 in N_2 @ 100 kPa (1.0 atm), and
- 21% O_2 in N_2 @ 280 kPa (2.8 atm).

Fuel/Oxidant Supplies. The amount of fuel and oxidant to be used in the proposed low-gravity smolder-suppression experiments is a critical science requirement because it influences not only how safely the experiment can be conducted, but also which fire conditions and their consequences are simulated. To date, the majority of low-gravity, solid-fuel combustion experiments, conducted or proposed, use a finite amount of fuel in a sealed container, with the air within the container serving as a finite oxidant supply.[1,6,17,18] Fuel supply has been made finite to limit the release of heat and products of combustion and to provide a guaranteed extinction mechanism. Oxidant supply has been made finite, yet in surplus of that required for complete combustion, to limit and contain the volume of contaminated atmosphere produced by the experiment. For example, in pioneering low-gravity experiments on the ignition and suppression of flammable materials, about 0.5 gram of fuel was burned in a 2×10^{-2} m^3 chamber, which provided an order of magnitude more oxidant than that required for complete combustion.[1]

The following will be the science requirements for the in-space experiments proposed here:

- The fuel supply will always be finite, with the amount burned determined by fire consequences.
- The oxidant supply will either be finite, to simulate the spacecraft condition wherein the fire zone has been isolated, or infinite, to simulate the condition whereby the fire zone has not or cannot be isolated and remains dynamically integrated with the environmental control and life support system.

Fuel/Oxidant Mixing and Rate. As with supply, fuel and oxidant mixing and rate have science requirements that are defined and compromised not only by the fundamentals of combustion and its suppression, but also aspects of practical application. The prerequisites for fundamental studies would favor in-space fire-suppression tests on diffusion-limited, quiescent combustion, whereas realistic simulation would favor tests with the low-velocity forced convection representative of manned spacecraft conditions. Because low-gravity experiments reveal that quiescent combustion is strongly influenced by the low-velocity convection that will be present aboard **Freedom**, the proposed in-space fire-suppression experiments will have to include both modes of fuel/oxidant mixing.[6,21,24] Furthermore, because the direction of convective oxidant flow has a strong influence over burning rate, the proposed tests should include both cocurrent and countercurrent flows, i.e., oxidant flows parallel and opposed to the flame spread, respectively. Note that the science requirements for oxidant supply and mixing are somewhat interdependent, as a finite supply would be associated with quiescent conditions, whereas infinite supply would be associated with flowing, convective (ventilated) conditions.

Ignition Event and Mode. The most probable ignition events in spacecraft operations are those from overheating of or sparks from a malfunctioning electrical system.[12] In almost all in-space combustion experiments conducted or proposed to date, ignition is accomplished by a one-time, point-source, high-energy event (electric spark) of short duration (milliseconds). Smoldering combustion, however, is typically initiated by a longer, more widespread, thermally based ignition event, which probably continues after smoldering begins.[6,18] For this reason, the science requirements for ignition in the proposed experiments will be initiation of smoldering combustion with the use of a hot-surface or radiant ignition system, whose temperature, size, and time-at-temperature can be independently controlled.

Reignition Tendency. Outside of the initial spacecraft fire and its consequences, there can be no more life- or mission-threatening event than a reignition after most, if not all, of the first-line of fire-fighting capability has been utilized. For this reason, suppressant and suppressant delivery systems will be evaluated not only on initial smoldering events, but also on subsequent ones, after some appropriate delay.

Fire Zone Size. A review of the available technical literature revealed that fires created for low-gravity experiments are sized as much for experimental convenience as they are for any other scaling property, such as the actual size of any fire.[6,13,18] This reasoning was considered sufficient for the experiments proposed here. Using the pioneering research of Summerfield and Martin[6] as a guide, the science requirements for fire-zone size are that the order of centimeters would be sufficient for fundamental (smolder wave/length ratio) and practical (incipient fire) reasons.

Fire Conditions. The studies of Task 1 indicated that the fire conditions of smoldering and flaming combustion represent the extremes over which suppressants would have to be effective. So far in this report, more emphasis seems to have been given to smoldering than to flaming combustion under low-gravity conditions. However, a review of the technical literature and the science requirements for fuel and oxidant indicate that the transition from smoldering to flaming combustion of a solid fuel may occur as the atmosphere is oxygen enriched.[6] Because such a transition may be inherent to the solid-fuel smoldering experiment designed here, no other contingency, such as an investigation of hydrogen flames, was considered for this science requirement, even though H_2 generated within the ECLSS could become the source of flaming combustion.[6,39]

Fire Lifetime. By the nature of the combustion event to be created and suppressed (smoldering), the duration of the experiments proposed here will be on the order of minutes to tens of minutes, up to about an hour.

Fire Consequences. By fire consequences are meant the temperature, amount of heat, and identity and quantity of chemical byproducts released by the experiment during the initiation and suppression of smoldering combustion. The science requirements for fire consequences were developed as an iterative process, dictated by fuel requirements. Thus, the consequences of deliberate smoldering during the experiments proposed here were predictable and predeterminable.

Suppressant Delivery. The science requirements for this experimental parameter included consideration of the suppressant to be delivered, the suppressant flow direction, and the amount of suppressant delivered. Based on the results of Task 1 (Section 2.0), the following was decided:

- CO_2, N_2, or H_2O will be delivered in a near-quiescent (low-velocity), countercurrent manner, such that the minimum volume required to suppress smoldering could be determined.

Because CO_2 and N_2 are gaseous fire suppressants, their dispersion is rather straightforward to accomplish experimentally. The dispersion of a mist of H_2O at low-gravity, however, represents an experimental challenge.[1,12] An effort was made here to understand and resolve this potential experimental design problem.

Atomization is conventionally accomplished by forcing a liquid (via high pressure) through a restriction. The end result of these simple mechanics is a high-velocity, very directional mist of liquid, whose momentum, flow rate, and droplet size are dependent on the backpressure applied. This end result has been shown to be unacceptable in low-gravity fire-suppression experiments.[1,41]

A review of the commercial literature revealed that a new atomization technology exists whose adoption here could solve the experimental problem regarding atomized-H_2O delivery. This technology, which relies on ultrasonics, generates fine mists (10-15 μm mean diameter) of water droplets with ultralow velocity at ultralow delivery rates that are a function only of the flow rate to the nozzle.[42] This novel atomization technology is to be incorporated into the in-space fire-suppression experiments proposed here, as it may have utility on a commercial, as well as a research, basis.

Diagnostics. To meet the science requirements for onboard diagnostics, basic thermochemical data on the pre-fire, fire and post-fire (smoldering) environments must be obtained in a straightforward manner, using simple, yet proven, techniques that are robust and reliable. The critical data to be monitored during the course of an "experiment" include gas (oxidant) and liquid (H_2O) flow rates, temperatures (gas and solid phase), and atmospheric chemical composition (O_2, CO_2, and CO). Concentration measurements include those of the initial atmospheric composition as well as the products of combustion and extinguishment. The proposed experiments lend themselves to diagnostic simplicity in terms of on-line data acquisition. Because carbon is the fuel and O_2/N_2 mixtures the oxidants, the only source of H_2O will be that deliberately delivered to suppress smoldering. The only source of CO will be smoldering carbon fuel. The other products of smoldering (CO_2 and O_2) would already be monitored under pre-fire conditions.

It is proposed that requisite fundamental data be obtained intermittently via the following techniques:

- Gas flow rates: mechanical meters,
- Liquid flow rates: piston pump,
- Temperatures: fine-wire thermocouples, and
- Atmospheric chemical composition: nondispersive infrared spectroscopy and solid-state sensing.

3.3.3. Scale of Experiments

The "scale of the experiment" is the extent of solid-fuel surface area creating the fire hazard, either under smoldering (quiescent) or "glowing" (forced-convection) conditions. The unique spacecraft environment guides the scaling of the proposed experiments. Space-borne experiments on combustion and its suppression differ from Earth-based ones in that consumable mission supplies of fuel, air, and fire suppressant are one-time available and that all byproducts must be contained onboard, and vented overboard only as a desperate, last resort. Furthermore, the amount of fuel and oxidant, fire-zone size, condition, and lifetime, and the number of ignitions, reignitions, and suppressions are dependent upon how and to what extent the consequences of the fire and post-fire conditions can be supported and accommodated by the spacecraft carrier. Spacecraft-carrier accommodations determine the maximum fuel/oxidant supply and supply rate, maximum electrical energy available, maximum volumetric space available, maximum acceptable rejected-heat load, and the identity and maximum volume of experiment byproducts.

Documents are available in the literature containing estimates on the limits of many of these accommodations for either the Spacelab aboard Space Shuttle[6,13] or for the Combustion Facility aboard Space Station.[17,18] These in-space laboratory data were used as guidelines to approximate the scale of the proposed experiments. These are summarized as follows:

- The maximum flow rate of fluid (oxidant and/or suppressant) to be supplied to combustion experiments aboard Space Station **Freedom** is about 65 l/min.

- The average electric power (at 28 V dc) to be made available is about 4 kW aboard Shuttle and about 6 kW aboard Space Station **Freedom**.
- The maximum volumetric space available for the combustion chamber is about 0.2 to 0.6 m^3.
- The maximum allowable heat load that can be dissipated by a combustion experiment is about 4 kW aboard Shuttle and about 15 kW aboard **Freedom**.
- The maximum allowable volumetric flow rate of "typical", "processable" products of combustion (CO_x, O_2, H_2O) from **Freedom** experiments is about 225 l/min at from 100 to 280 kPa (1.0 to 2.8 atm).

These estimates for in-space combustion-experiment accommodation were compared to the properties of the candidate fuel, carbon, and its combustion products, to determine which ones were limiting. These carbon fuel and combustion properties are listed in Table 3.6 (also see Table 3.5 and the references therein).

TABLE 3.6. CARBON FUEL AND COMBUSTION PROPERTIES

- Elemental content: carbon, trace ash
- Carbon density: ~1.1 g/cm^3
- Heat content: 33 MJ/kg
- Stoichiometric air requirement: 9.4 l/g
- Ignition temperature: ~500 C
- Ignition energy: 1-4 W/cm^2
- Smoldering combustion temperature: ~500 C
- Smoldering combustion rate: ~1×10^{-4} g/cm^2-sec
- Glowing combustion temperature: ~950 C
- Glowing combustion rate: ~2×10^{-3} g/cm^2-sec
- Products of smoldering or combustion: CO_x
- Volumetric products of smoldering or combustion: 9.4 l/g

In Table 3.6, smoldering combustion refers to quiescent conditions; glowing combustion refers to forced-convection conditions.

The analysis of carbon properties compared to experiment accommodations showed that fluid-flow (oxidant) constraints aboard possible spacecraft carriers allow carbon fuel to burn (stoichiometrically) at a maximum rate of about 7 g/min. Based on the maximum estimated burning rate for the carbon fuel, about 0.12 g/cm^2-min, which would occur under forced-convection or "glowing" conditions, the maximum allowable solid surface available for combustion would be about 58 cm^2.

The above estimate of the maximum solid surface area available for combustion is very likely conservative because the maximum carbon burning rate used in the calculation was that estimated under terrestrial conditions, which, from what is known about solid-fuel burning at low-gravity, may be artificially high by about a factor of 2. Thus, a nominal factor of about 2 can be used to increase the available solid-fuel burning surface area to as much as 100 cm^2, which is a more workable number in experimental design. Given that the fire zone size should be on the order of centimeters, the scale and shape of the smoldering combustion zone could vary from 10 cm-a-side, if the geometry were square, to 11.3 cm in diameter, if the geometry were circular.

Multiple independent combustion experiments, or fire zones, could be simultaneously accommodated by possible spacecraft carriers. Thus, the scale of any one experiment would best be determined using as a guide the total number of experiments that should be conducted to reproduce results and to evaluate certain parameters over acceptable ranges.

3.3.4. Number and Duration of Tests

It is simply not prudent to evaluate all, or even many, of the potential fire suppressants available under all, or even many, of the types of fire conditions possible. Therefore, it was the underlying intent of this project to define the least number of definitive experiments that would yield the most critical and timely data. A description of the minimum parametric variations for the first round of in-space tests, based on the preceding discussions, follows:

- Only one carbon fuel (which fixes the thermophysical properties of the fuel) would be used.

- Four nitrogen-oxygen atmospheres would be used to represent different spacecraft habitats.

- Fuel supply would be finite.
- Two oxidant-supply conditions would be used: quiescent and finite, and dynamic and replenishable.
- Ignition would be induced using an appropriately sized electrically heated surface operating for a fixed time at one temperature above that required for ignition.
- Two ignition times would be used: first, to begin the smoldering, and second, to reignite the smoldering after it apparently had been suppressed.
- One fire-zone size (centimeters) would be used, which would be established from the total number of critical first-round experiments identified (to be defined).
- Two fire conditions would be evaluated: smoldering combustion under a quiescent atmosphere, and glowing combustion under a dynamic atmosphere.
- The fire lifetime would be of the order of minutes to an hour, to encompass ignition, burning, suppression, reignition (in some cases), and resuppression.
- Fire consequences of byproduct release would be controlled and fixed by the other experimental parameters, particularly the fuel.
- Six different suppressant delivery conditions would be evaluated to accommodate three suppressants, CO_2, H_2O, or N_2, either at two different premixed concentrations in the quiescent atmosphere or at an increasing concentration in the dynamic atmosphere, until the volume required to cause suppression was reached.
- Centralized diagnostic equipment for temperature and gas composition measurement would be operated and the data multiplexed during all phases of the in-space smolder-suppressant experiments.

Table 3.7 summarizes the parametrics just listed to show the total number of first-round experiments required to obtain data on all possible variations. The product of the minimum number of first-round experiments is 192. Two- or possibly three-times this minimum number of experiments (~400-600), however, could be necessary to determine experimental probability of occurrence and reproducibility. This impractical number of experiments demonstrates the need to conduct multiple experiments simultaneously.

TABLE 3.7. PARAMETRICS OF PROPOSED IN-SPACE SMOLDER-SUPPRESSION EXPERIMENTS

Experimental Parameter	Minimum Number of Discrete Variations
Fuel	1
Oxidant	4
Fuel supply	1
Oxidant supply	2
Ignition mechanism	1
Ignition/reignition	2
Fire-zone size	1
Fire conditions	2
Fire lifetime	1
Fire consequences	1
Suppressant delivery	6
Diagnostics	1
Total Experimental Combinations:	192

A practical approach for multiple experiments is suggested. The experiment package should consist of a centralized combustion isolation chamber, serviced and monitored by a common oxidant/suppressant supply, exhaust, and diagnostic system, into which could be mounted a variable number (up to some maximum) of independent fuel canisters, each insulated and containing a fixed charge of carbon prefitted with an integral ignitor and array of thermocouples. The design problem is thereby reduced to determining the number of "experiments" that could be conducted simultaneously, which is a function of the mass, volume, and geometry of the unit-charge of solid fuel.

Although the scale, number, and duration of simultaneous low-gravity smolder-suppression experiments can be fixed solely by limitations imposed by spacecraft-carrier accommodations, it was thought prudent to attempt to factor in the design details and experience from standardized smolder-suppression experiments at normal gravity. Available information on a terrestrial experimental analog comes from an industrial standard for the evaluation of the suppression of smoldering Class A (solid) fuels using charcoal cubes (2.5 cm-a-side) in tests that last about 1 hour, or less.[29]

All the information on what might be done in space and what has been done on Earth was then integrated to arrive at the following experiment specifications:

- The carbon fuel element whose smoldering is to be suppressed should be a rectangular parallelepiped in geometry, 2 x 2 x 15 cm in dimension, and about 60 grams in weight, which would allow up to 25 separate experiments of about 1 hour, or less, in duration to be conducted simultaneously in space.

- The elapsed time required at low gravity, not counting pre- and post-experiment activities, would be about 16 hours, based on 25 separate experiments in an hour and 400 total tests (twice the minimum requirement).

3.3.5. Selection of Priority Experiments

Table 3.8 lists those 8 of the 192 experiments whose results were thought most crucial and timely to the NASA spacecraft fire-safety program. These priority experiments have been characterized in terms of critical variables, with other key adjustable parameters held constant, at worst-case conditions. For example, oxidant would be supplied in a dynamic, cocurrent, and replenishable manner to promote smoldering, to possibly make it more difficult to suppress, and to simulate the spacecraft cabin environment (low-velocity ventilation). Suppressant would be supplied in a dynamic, countercurrent, and replenishable manner to determine if its delivery intensified the smoldering, which with respect to the origin of suppressant, would appear to be deep-seated.

The reason for each priority experiment is as follows:

- Experiments No. 1 and 2 are intended to be shakedown tests of the systems to induce smoldering in low-gravity "air" atmospheres and to provide data on the effectiveness of the leading candidate for spacecraft fire suppression, CO_2, and its delivery system.

- Experiments No. 2, 3, and 4 are intended to provide data on the comparative effectiveness of CO_2, N_2, and H_2O as suppressants and to test the ultrasonic H_2O-delivery system.

TABLE 3.8. PRIORITY LOW-GRAVITY SMOLDER-SUPPRESSION EXPERIMENTS

Experiment No.	Atmospheric O_2 Content (%)	Atmospheric Pressure (KPa)	Inerting Agent	Suppression Agent
1	21	100 (1 atm)	None	None
2	21	100 (1 atm)	None	CO_2
3	21	100 (1 atm)	None	N_2
4	21	100 (1 atm)	None	H_2O
5	16	100 (1 atm)	N_2	None
6	16	100 (1 atm)	N_2	Best Nos. 2-4
7	21	280 (2.8 atm)	None	None
8	21	280 (2.8 atm)	None	Best Nos. 2-4

- Experiments No. 5 and 6 are intended to provide information on whether N_2-inerting of the atmosphere prevents smoldering, and if not, if such inerting influences the effectiveness of the best among CO_2, N_2, or H_2O to suppress smoldering, once initiated, respectively.

- Experiments No. 7 and 8 are intended to provide hyperbaric systems data on more intense (glowing) smoldering, possibly flaming, and data on how effective the best among CO_2, N_2, and H_2O is at suppressing this type of spacecraft fire.

3.4. Other In-Space Experiment Considerations (Question No. 3)

3.4.1. Justification for In-Space Testing

The conduct of the proposed experiments in space, as opposed to ground simulation, is justified because nowhere, but in an orbiting spacecraft, can a low-gravity environment be provided for the minimum duration of exposure, minutes to an hour, required for the effective testing of terrestrial agents to suppress smoldering.

3.4.2. Influence of Low-Gravity Quality

By low-gravity quality is meant the approximate maximum residual gravity, and acceleration fluctuations (g-jitter) experienced in the tests. It is the opinion of the author, from a review of the available technical documents on a proposed modular combustion facility for the Shuttle and the Space Station **Freedom**, that the residual gravity and g-jitter experienced aboard Space Shuttle and expected aboard Space Station **Freedom** should have a negligible effect on smoldering combustion experiments.[6]

3.4.3. Volume and Power Estimates

The objective of this activity was to provide first-order estimates for the maximum and minimum volume and power requirements of the proposed in-space smolder-suppression experiments.

The volume and power requirements of the proposed in-space smolder-suppression experiments are dependent upon in which space carrier the experiment will fly (Shuttle or **Freedom**), and whether the experiment is intended to be a stand-alone device or be incorporated into either an already designed in-space experiment (e.g., droplet burning) or a dedicated facility (Shuttle Spacelab or **Freedom** Modular Combustor). Given the urgency to acquire the test data, it is very probable that the proposed experiment will be integrated into existing low-gravity combustion experiments or facilities.

If the integration-option is exercised, the principal hardware add-on will be the modular solid-fuel canister(s), which would number from one to 25. The minimum volume and power requirements of the proposed experiment would therefore be defined by the volume and power required by one fuel canister, and the maximum by 25. The volume of one modular solid-fuel canister is estimated to be about 1×10^{-3} m^3, which could be accommodated by all proposed spacecraft carriers. The volume of 25 modular solid-fuel canisters is about 2.5×10^{-2} m^3, which could be readily accommodated by the spacecraft carrier with the most available volume, the Space Station **Freedom** Combustion Facility (0.6 m^3).

The corresponding minimum (1 solid-fuel canister) and maximum (25 solid-fuel canisters) power requirements for the proposed experiments are about 0.06 and 1.5 kW, respectively, which can readily be accommodated by either the Shuttle (4 kW) or the Space Station **Freedom** (6 kW).

3.4.4. Crew Involvement

Crew time aboard orbiting spacecraft is precious. Because of this fact, and that a payload specialist would probably not be dedicated to these fire-safety experiments, it would be in the best interest of the mission to automate the proposed smolder-suppression experiments as much as possible. Given the straightforwardness of the design and operation of the experiments, near-complete automation should not be difficult. The only prerequisite crew involvement anticipated would result if a payload specialist were to have to replace any number of "spent" fuel canisters to proceed with a second round of tests during the same mission. The effort involved to do this should be minimal, given the modular design of the experiment.

3.5. Concluding Remarks on Experimental Definition and Requirements (Task 2)

The objective of Task 2 of this project was to define the science requirements for and justify the in-space conduct of experiments designed to evaluate selected (Task 1) concepts for fighting smoldering fires aboard manned spacecraft. Promising concepts included suppression by local application of CO_2 or H_2O, and prevention by atmosphere inerting with N_2.

Presented here are details on the conceptual design and operation of a critical set (8 out of 192 possible combinations) of feasible, straightforward, versatile, and scalable experiments expected to yield timely, definitive, and practicable information on fire suppressants and suppressant delivery systems under realistic spacecraft-fire conditions. Specifics are provided on the experimental parameters of solid fuel (carbon), oxidant (habitable spacecraft atmospheres), fuel/oxidant supply, mixing mode, and rate (quiescent and finite; ventilated and replenishable), ignition mode, event, and tendency, fire-zone size, fire conditions, lifetime, and consequences (toxicity), suppressant and suppressant delivery system, and diagnostics. Moreover, the scale, number, and duration (about 1 hour) of the proposed low-gravity experiments were estimated using not only data on the limitations imposed by spacecraft-carrier (Shuttle or Space Station **Freedom**) accommodations, but also data on the details and experience of standardized smolder-suppression experiments at normal gravity. Deliberately incorporated into the conceptual design was sufficient flexibility, scalability, and interchangeability for the prototype experimental package to fly either on Shuttle now or **Freedom** later. This flexibility is provided by the design concept of up to 25 modular fuel canisters within a containment vessel, which permits both integration into existing low-gravity in-space combustion experiments and simultaneous testing of separate experiments to conserve utilities and time. This modular construction is vital because some of the critical in-space fire-suppression experiments designed in this program may have to be flown aboard Shuttle to acquire data vital to the design of **Freedom**.

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4.0. DEFINITION COMPLETION AND IMPLEMENTATION PLAN FOR SPACECRAFT FIRE-SUPPRESSION EXPERIMENT

This section presents the results of Task 3 efforts on the project. The specific objective of Task 3 was to complete the definition of the proposed in-space fire suppression experiments and to prepare an implementation plan.

4.1. Information Sought

As in the preceding tasks, the efforts of Task 3 were approached by seeking technical information, interpretations, and logic to provide answers to critical questions. The critical issues for Task 3 are listed in Table 4.1.

TABLE 4.1 CRITICAL QUESTIONS ON DEFINITION COMPLETION AND IMPLEMENTATION PLAN

No.	Critical Issues
1.	What criteria should guide the determination that the proposed in-space smolder-suppression experiment had reached the milestone of "definition", and had this milestone been reached?
2.	What criteria should guide suggestions for in-space installation, and what is the result of this analysis?
3.	How realistically and to what extent could estimates be made for the engineering-development implementation plan, including future design efforts, precursor testing, time and labor schedules, and order-of-magnitude costs?

4.2. Criteria for Establishment of Definition (Question No. 1)

A condensation of the requirements of NASA program solicitations, announcements of opportunity, and research announcements established the overall objective for the proposed in-space experiments. Basically, the NASA programs (including the OAST IN-STEP solicitation that sponsored this effort) seek to broaden the cooperative participation of the U.S. academic and industrial community in low-gravity basic research and applied technology development by making available and exploiting the unique manned-orbiting-laboratory capabilities of the Space Station **Freedom**, with the intent of maintaining, building, or rebuilding world leadership in Earth-based advanced technology. The pace and timing of the cooperative participation seek to define and develop in-space technology experiments to be carried-out aboard Space Station **Freedom**, once it is operational in the mid-to-late 1990s. However, the nature and consequences of the in-space technology of concern here, spacecraft fire safety, portends a different, more urgent, and less certain mode, pace, and timing of participation. Because the results of the proposed low-gravity smolder-suppression experiment appear vital to the safety of the Space Station mission itself, they probably should be acquired as **Freedom** is designed and before it is built, implying that the in-space experiments proposed here should be carried-out aboard **Space Shuttle** or other existing low-gravity carriers (getaway specials, free flyers).

Thus, the criterion for determining that the proposed experiments are adequately defined for the needs of NASA is the conception of the least common denominator in unit experiment design that would be adaptable to either Shuttle or **Freedom** spaceflight, and modular so that a different number of tests could be performed at any time aboard either carrier. In this regard, the author is confident that the conceptual design given in Section 3.0 of this report provides the criterion for the "definition" for the in-space smolder-suppression experiment.

4.3. Paradigm of In-Space Smolder-Suppression Experiment (Question No. 2)

The design characteristics and operating parameters for the proposed in-space fire-suppression experiment plan, presented in Sections 2.0 and 3.0, have established some quantitative features, at least to a first order. These features are summarized in three charts. Table 4.2 lists the general design characteristics of the suggested experiment plan. Table 4.3 lists the general operating characteristics of the experiments, describing proposed techniques for 8 critical experiments out of a matrix of 192 combinations of parameters (see Table 3.8 in Section 3.0). Experiments No. 1 to 4 are tests under a normal "air" atmosphere to investigate smoldering both without suppression (No. 1) and with suppressing agents of CO_2, N_2, and H_2O (Nos. 2 to 4). Experiments No. 5 and 6 are tests under a reduced O_2 atmosphere to investigate

TABLE 4.2. CONCEPTUAL DESIGN OF SPACECRAFT FIRE-SUPPRESSION EXPERIMENT PACKAGE

General Design Characteristics
• Each fuel element will consist of a 2 x 2 x 15 cm, 60-g bar of carbon, into one square-end of which is imbedded an electrical-resistance heated ignition surface, and into the vertical length of which are imbedded beaded thermocouples at 1-cm intervals along the centerline, beginning at the ignition zone.
• Each carbon fuel element will be suspended within an excavated and insulated canister such that a 1-cm gap surrounds the element about its length and about 5-cm about each square end.
• Fuel canisters will also be parallelepipeds and clustered together in a honeycomb array to conserve volume within a second "isolation" chamber.
• Each fuel canister will have individual inlet and exhaust valves and transfer lines at both ends, which will originate on the inside walls of the isolation chamber and which will be individually connected to a common fluid supply and recovery system.
• The fluid supply system will consist of individual pressurized canisters of oxidizer (O_2) and of gaseous suppressant (CO_2 and N_2), and a reservoir of deionized H_2O equipped with a low-flow pump.
• The fluid recovery system will be an evacuated chamber equipped with a prefilter of activated carbon, which will be used as a holding tank before the products of smoldering and its suppression are processed by the spacecraft environmental control and life support system.
• For all tests involving H_2O, the suppressant inlet valve will consist of an ultrasonic atomizer.
• Fluid supply and recovery transfer lines to individual canisters will be manifolded to a common instrument diagnostic package, which will periodically scan a sample from each ongoing experiment.

passive inerting with increased N_2 in the atmosphere. In Experiment No. 6, the best of the three active suppressants evaluated in Experiments No. 2 to 4 will also be investigated in combination with the inerting atmosphere. Experiments No. 7 and 8 are tests under a hyperbaric (280 kPa total pressure) atmosphere, with no suppression and with the best of the three agents, respectively. Table 4.4 lists some of the provisions for simplicity, safety, flexibility, scalability, and interchangeability that have been incorporated into the conceptual design of the experiment plan.

In summary, an experiment plan is proposed, consisting of the initiation and attempted suppression of smoldering in a fixed amount of carbon fuel suspended in a fuel canister. The concept is further illustrated by the sketch in Figure 4.1, which is a functional diagram to represent the features

TABLE 4.3. CONCEPTUAL OPERATION OF SPACECRAFT FIRE-SUPPRESSION EXPERIMENT PACKAGE

General Operating Characteristics
• Fuel canisters will remain evacuated until the experiment (smoldering) is to be initiated.
• Each experiment will commence with the injection of oxidant into the fuel canister at the specified O_2/N_2 ratio, pressure, and ventilation rate (about 0.1-0.5 cm/sec).
• Oxidant and, in Experiments No. 5 and 6, inertant will be injected at the ignition end of the fuel element to create coflow conditions (oxidant flow and smoldering wave unidirectional).
• Each experiment will then be continued by activating the hot-surface ignitor until the diagnostics detect the thermal-wave characteristics of smoldering propagating down the length of the fuel element and the evolution of CO and CO_2 [Experiment No. 1 will calibrate the smoldering process at low gravity in terms of time (t), temperature (T), heating rate (dT/dt), and byproducts (CO/CO_2)].
• After smoldering has been achieved and calibrated using air as an oxidant (Experiment No. 1), metered amounts of CO_2 (No. 2), N_2 (No. 3), and H_2O (No. 4) suppressant will be introduced into the fuel canister at the end opposite the ignitor until smoldering is impeded (dT/dt slowed, CO/CO_2 increased), at which time the concentration will be held constant to determine if the smoldering can be suppressed and how long it takes to do so.
• The agent among CO_2, N_2, and H_2O requiring the lowest concentration to suppress smoldering in the least amount of time will be evaluated in Experiments No. 6 and 8.
• Experiment No. 6 will not be conducted if smoldering is not achievable in Experiment No. 5, where nitrogen-enriched air might act as an inertant.
• Input and exhaust of each fuel canister will be periodically analyzed by the common diagnostic system throughout the course of an experiment.
• The fuel canister will be purged with N_2 and evacuated to ensure suppression, whether smoldering has (dT/dt to zero) or has not been suppressed by the introduction of agent.

described in Table 4.2. The illustrated carbon-fuel canister is one of a possible array of up to 25 that may be clustered within an isolation chamber designed, for example, to fit within a **Freedom** laboratory rack. The interchangeable fuel canisters would have common access to oxidant and suppressant supply and exhaust.

The proposed characteristics and design illustrations offer a feasible approach to meet the definition and critical requirements for an in-space experiment. While the proposed experiment plan owes some commonality to previous concepts recently appearing in the literature,[1-3] it is innovative in that it is based on a thorough analysis of priority needs, low-gravity

TABLE 4.4. OTHER CONTRIBUTING FACTORS TO SPACECRAFT FIRE-SUPPRESSION EXPERIMENTS

Simplicity, Safety, Flexibility, Scalability, and Interchangeability
• The 1-dimensional geometry of the smoldering process is amenable to modeling.
• Oxidant will not be introduced into the evacuated fuel canister until the experiment is intended to start, primarily to avoid smoldering after an accidental ignition and subordinately to avoid "weathering" and subsequent alteration of carbon reactivity.
• The supply of all oxidizing agents, O_2, CO_2, or H_2O, can be independently shut off during smoldering, and the canister purged with a non-oxidizing agent, N_2, at either or both ends, to stop the smoldering of the finite amount of fuel.
• The isolation chamber offers double-hull containment redundancy to the experiment, should a "hot" fuel canister develop a leak.
• Any leaks from the smolder-suppression tests are non-corrosive and compatible with the spacecraft environmental control and life support system (ECLSS).
• The exhaust recovery chamber acts as a holding tank to buffer the ECLSS.
• The fuel and diagnostics are interchangeable with the flammable solids and detectors proposed for other micro-gravity combustion experiments.
• The experimental package can be tested and calibrated on the ground at normal gravity, without modification.
• The scale of any sequence of experiments is controlled by the number of fuel canisters allowed to smolder at one time, allowing it to be accommodated by different spacecraft carriers.

combustion science, and experimental requirements, as discussed in Sections 1.0 through 3.0. It must be recognized, however, that the configuration of the isolation chamber and diagnostics and accommodation packages is preliminary. More detailed and refined designs cannot and should not be established at this time. The concept of modular elements in any of several geometric arrays is most promising, nevertheless, and this feature is very likely to be essential to the eventual design.

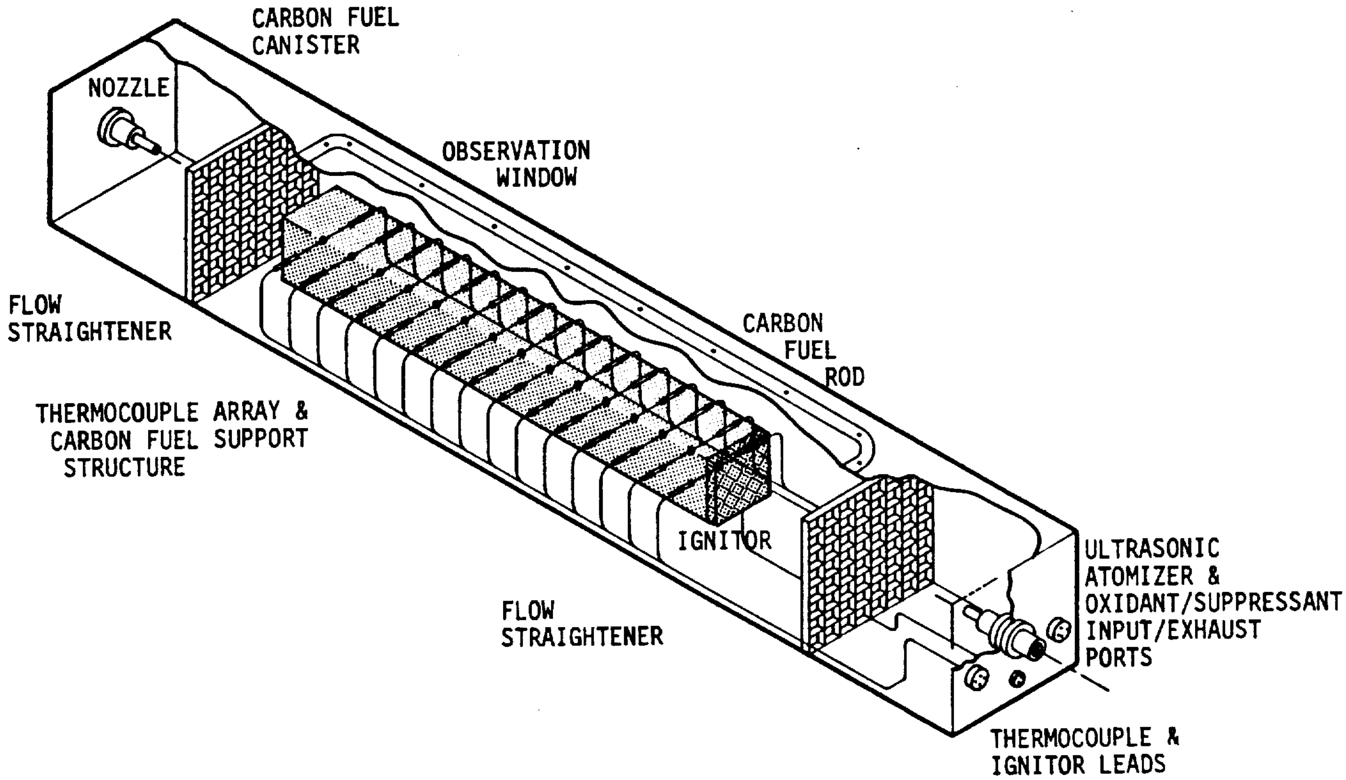

FIGURE 4.1. FUNCTIONAL DIAGRAM FOR THE IN-SPACE SMOLDER-SUPPRESSION EXPERIMENT

4.4. Implementation Plan (Question No. 3)

This section presents a preliminary implementation plan for the next possible phase of this project involving the engineering **development** of the proposed in-space experiments.

The remainder of this project, if continued, would be carried out in accordance with established NASA practice, which nominally consists of the following sequential activities:

- Project Definition: Conversion of conceptual systems designs into optimized, technically unique engineering designs to lead to a project plan and conceptual design review.
- Non-Advocate Review: Final analyses of designs to determine likelihood that the flight experiment will achieve objectives.
- Hardware Design and Development: Completion and development of design, with appropriate precursor testing.

- Critical Design Review: Qualification of functional hardware and safety procedures and data package.
- Pre-ship Review: Assessment of flight hardware readiness.
- Payload Integration: Adaptation of experiment into carrier and final scheduling.

The first activity, the Project Definition phase, is the obvious, crucial follow-up to lead to the Non-Advocate Review, which is the official go-ahead to proceed to a flight program. An implementation plan is thus necessary to guide the requirements for the eventual engineering-development phase of this project. Given the uncertainty regarding the identity of the spacecraft carrier, one cannot formulate the details of any implementation plan for the entire experiment. Because of the manner in which the proposed experiment has been conceived, however, it is suggested that designs, development, and ground-based precursor testing could proceed without delay on the unit experiment (carbon fuel-rod and canister) prior to its integration with any sized/shaped isolation chamber and with either its own or the spacecraft carrier's accommodation and diagnostics systems. As a consequence, the author proposes that the implementation plan for the proposed in-space smolder-suppression experiments be conducted in a phased manner, initiated by constructing prototype carbon fuel-rods and canisters followed by subjecting them to laboratory shakedown tests under normal-gravity conditions.

Realistic monetary and time budgets for the total experiment-development phase of the implementation plan beyond the Non-Advocate Review are estimated to be about $1 to 1.5 million and 12 to 15 months, respectively. The budgets for the essential precursor experiments, ground-based testing of a prototype of the carbon-molder canister, are estimated to be about $200 to 300 thousand and 5 to 7 months. The quoted prices and schedules represent order-of-magnitude estimates, for the purposes of this study, but they can readily be made more firm and specific in the next phase of project definition.

4.5 Concluding Remarks on Definition Completion and Implementation Plan (Task 3

The objective of Task 3 was to complete the definition of the proposed in-space fire-suppression experiments and to discuss the future needs and progress for the accommodation and scheduling of the experiments. The basic experiment concept is that of a modular carbon fuel element with ignitor and thermocouple instrumentation. One to 25 elements would be mounted in a containment chamber with common utilities to supply each canister with oxidant and suppressant, and to remove exhaust.

The proposed experiment meets the definition of an in-space experiment for integration on the Shuttle or the Space Station **Freedom.** Furthermore, the proposed experiment can provide vital safety information relevant to the design of the **Freedom** itself. The experiment concept is illustrated by listing quantitative design factors and operational procedures, although these features are preliminary at this level of progress.

The primary thrust of this project has been in the review of suppression concepts and in the definition of experiments and their science requirements; these occupied most of the total effort, as reported in the Task 1 and 2 findings. The implementation plan presented here is a generic outline of the necessary follow-on activities. It is recognized that much more detail is needed to initiate the subsequent engineering development.

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Report Documentation Page

1. Report No. NASA CR 185295	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Definition of Experiments to Investigate Fire Suppressants in Microgravity		5. Report Date December, 1990
		6. Performing Organization Code G1424-0000 (746)
7. Author(s) James J. Reuther		8. Performing Organization Report No. BCO-JJR-90-1348
		10. Work Unit No. 506-48-4A
9. Performing Organization Name and Address Battelle 505 King Avenue Columbus, Ohio 43201-2693		11. Contract or Grant No. NAS3-25362
		13. Type of Report and Period Covered Contractor Report Final
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191		14. Sponsoring Agency Code

15. Supplementary Notes

Project Manager, Robert Friedman, Space Experiments Division
NASA Lewis Research Center

16. Abstract

Defined are the conceptual design and operation of a critical set of experiments expected to yield information on suppressants and suppressant delivery systems under realistic spacecraft-fire conditions (smoldering). Specific experiment parameters are provided on the solid fuel (carbon), oxidants (habitable spacecraft atmospheres), fuel/oxidant supply, mixing mode and rate (quiescent and finite; ventilated and replenishable), ignition mode and event, fire-zone size, fire conditions, lifetime, and consequences (toxicity), suppressants (CO_2, H_2O, N_2) and suppressant delivery systems, and diagnostics. The scale, number, and duration of proposed low-gravity experiments were estimated using data not only on the limitations posed by spacecraft-carrier (Shuttle or Space Station Freedom) accommodations, but also data on the details and experiences of standardized smolder-suppression experiments at normal gravity. Deliberately incorporated into the design was interchangeability provided by the concept of using up to 25 modular fuel canisters within a containment vessel, which permits both integration into the existing low-gravity in-space combustion experiments on either the Shuttle now or Freedom later and simultaneous testing of separate experiments to conserve utilities and time.

17. Key Words (Suggested by Author(s)) Spacecraft Fire Safety Smoldering Combustion Fire Suppression Shuttle and Space Station		18. Distribution Statement Unclassified-Unlimited Subject Category 18	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No of pages 62	22. Price* A04

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service, Springfield, Virginia 22161